The MEMS Flux Concentrator: A Device for Minimizing *1/f* Noise in Magnetic Sensors

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Abstract
Magnetic sensors typically have a considerable amount of 1/f noise that limits their performance in detecting slow-moving military vehicles. Here we describe a Micro Electro-Mechanical Systems (MEMS) flux concentrator, which is a new device that can minimize 1/f noise in magnetic sensors by modulating the magnetic field at the position of the sensor. The modulation is accomplished by a periodic motion of flux concentrators on each side of the magnetic sensor. Modulating the sensor field shifts the operating frequency to higher frequencies where the 1/f noise can be one or two orders of magnitude smaller. We will also present magnetic and mechanical modeling results on a design that will operate at 29 kHz.

Though *1/f* noise occurs in electronic devices, it also occurs in a variety of other places.[1] For example, it also occurs in the stock market, emissions from quasars, highway traffic, the global temperature, and the flow of the river Nile. The subject of *1/f* noise in solid-state microstructures has been review by Kirten and Uren[2]. Most magnetic devices, such as magnetic sensors[3-5], also have a considerable amount of *1/f* noise due, primarily, to domain wall motion. In the case of spin dependent tunneling sensors, charge trap sites in the barrier[6] and near barrier metal interfaces are also noise sources. The noise in the case of magnetic sensors is often strongly magnetic field dependent.

For some applications the performance of magnetic sensors is severely limited by *1/f* noise. For example, *1/f* noise is a particularly serious problem in using magnetic sensors to detect slowly moving vehicles, since the frequency region of interest is less than 1 Hz. To make matters worse some of the new types of sensors, such as GMR and spin dependent tunneling sensors, have more *1/f* noise than AMR or other more mature types of magnetic sensors. For electronic or magnetic devices, there is often a “knee” in the curve of noise versus frequency below which *1/f* noise begins to dominate the Johnson noise. For spin dependent tunneling sensors this knee may occur at a frequency larger than 10 kHz. It is likely that this knee will move down in frequency if the quality of the junctions can be improved. Currently, *1/f* noise is clearly a significant problem in detecting signals at frequencies less than 1 Hz. Even if improved spin dependent tunneling sensors have less *1/f* noise, it is clear that *1/f* noise will remain a serious problem in magnetic sensor technology.

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Flux concentrators[7] are appropriately shaped soft ferromagnets with a high permeability that are used to increase the magnetic field at the position of sensors by a factor from about 10 to 100. Here we discuss a microelectomechanical systems (MEMS) device that combines a magnetic sensor and flux concentrators in a new way. The device that we call a MEMS flux concentrator can mitigate the problem of *1/f* noise in magnetic sensors. Figure 1 shows a schematic picture of the device. What is unusual in our new device is that, instead of using stationary flux concentrators, we will deposit the flux concentrators on

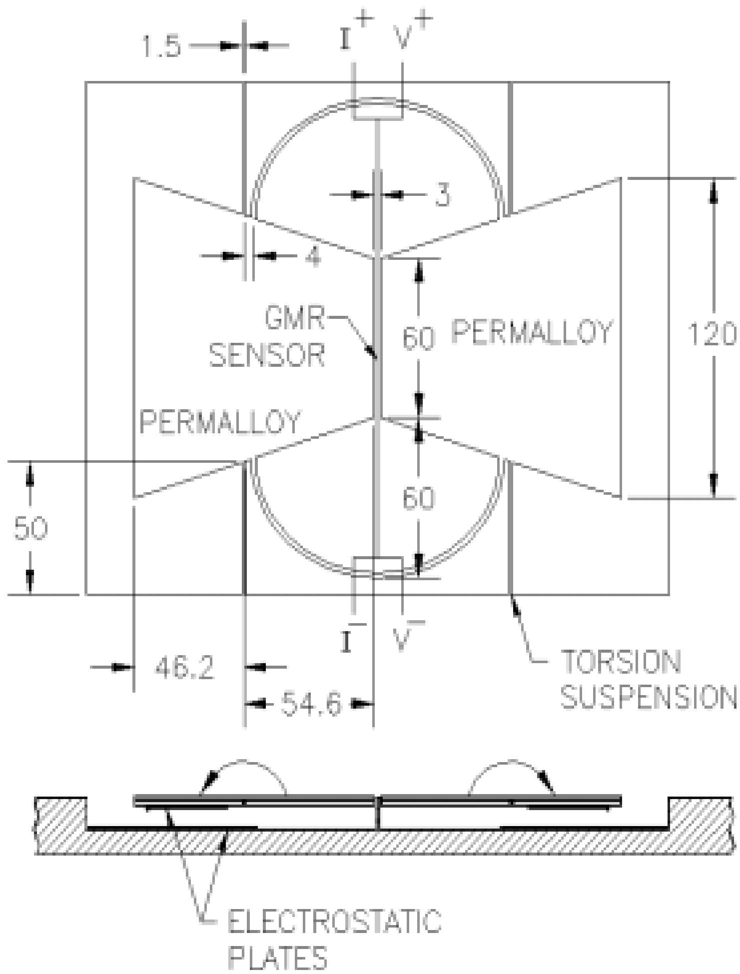

Figure 1. Schematic drawings of the MEMS flux concentrator that depicts the MEMS flap covered with permalloy, the magnetic sensor, and the electrostatic plates which drive the motion. All the dimensions are in microns.

MEMS flaps. By driving the flaps to perform oscillatory rotation about the torsional suspension at a frequency f_m, we will be able to modulate the field at the position of the sensor at a frequency above the knee in the noise versus frequency curve for the sensor. Each time the flap passes through its horizontal position, the field at the position of the sensor will be have its maximum value. As a result, the sensor will see a magnetic field

modulating at a frequency $2f_m$. The advantage is that the operating frequency for the sensor can be set above the knee in the noise versus frequency curve and, thus, the noise will be reduced. The torsional suspension is positioned so that the moments of inertia on each side are equal to minimize the stress on the suspension when the MEMS flaps are in motion. The signal from the sensor will be amplified by a relatively narrow band amplifier operating at the frequency $2f_{m.}$ The low frequency signal can then by extracted by demodulation. The bandwidth of the amplifier should be large enough to include the low frequencies of the original signal. This is not a difficult requirement to fulfill since the signal frequencies will typically be less the than a few Hz.

The design requirements are: (1) The flux concentrator should enhance the field to be measures by a factor greater than 2. (2) The amplitude of the field modulation should be greater than 30%. (3) This modulation should be achieved without having to apply too large a voltage to the electrostatic plates. (4) The frequency $2f_m$ should be above the knee in the noise versus frequency curve. (5) Not too much energy should be required to drive the motion.

Magnetic and mechanical modeling was performed to obtain a design that is likely to satisfy these operational requirements. The following is a description of the design. The MEMS flaps and the torsional suspension depicted in Fig. 1 will be 1 micron thick polysilicon. Polysilicon was chosen because of the maturity of the MEMS processing technology that is available for this material. The MEMS flaps will be covered with a ½ micron layer of permalloy. The motion of the MEMS flaps will be driven electrostatically by applying a voltage between the electrodes depicted in Fig. 1. To minimize the amplitude of the electrostatic drive voltage, the drive frequency should be equal to the resonance frequency of the flaps. It is necessary that the flaps move in phase with one another. It will be difficult to fabricate the two MEMS flaps and torsional suspensions so that the two flaps have the same resonant frequency. Because of this, keeping the motion of the two flaps in phase is not a simple task. This difficulty can be overcome by including mechanical coupling between the flaps using the polysilicon arc bridges shown in Fig. 1. With this coupling the lowest frequency motion is the normal frequency motion in which the flaps move in phase with one another.

The mechanical modeling was performed using a commercial finite element code, Ansys, to determine the torque required to obtain a given rotation of the flaps and to determine the normal mode resonant frequencies. In the calculation, the constants used were 160 GPa for the bulk modulus of polysilicon, 207 GPa for the bulk modulus of permalloy, a Poisson's ratio of 0.2 for the polysilicon, and a Poisson's ratio of 0.3 for permalloy. The three lowest resonant frequencies are 28.646 kHz, 31.756 kHz and 39.852 kHz. The lowest frequency motion is the in phase motion of the two flaps. This frequency is high enough to be above the "knee" in the noise versus frequency curve. To obtain 3 microns of motion of the edge of the flap near the sensor, the torque required per plate is 1.31 μN.

The voltage V that must be applied to the electrostatic plates to obtain a torque of 1.31 μN can be estimated. Consider two plates of length L and of width w separated by a distance $d << L$ that is hinged at one end so that it can rotate. If a voltage is applied, the torque τ bringing the plates together is given by

$$\tau = \frac{\varepsilon_o V^2 w}{2\theta^2}\left\{\frac{L\tan\theta}{d - L\tan\theta} + \ln\left[1 - \frac{L\tan\theta}{d}\right]\right\} \qquad (1)$$

where θ is the angle of rotation. One sees that the torque approaches infinity as the plates approach one another. Using this equation, at $\theta = 0$ if the separation d is 4 microns, the voltage required to produce 1.3 μN torque is approximately 52 volts. Because the torque increases with increasing θ, 52 volts is an upper bound. Further, this estimate does not consider the effect of the Q of the device. Since the voltage required to obtain a given amplitude for the motion is proportional to $1/\sqrt{Q}$, a much lower voltage can be used if Q is large when the device is driven at the resonant frequency. The Q will be primarily limited by air friction if the motion is in air. If the device is vacuum packaged, the Q can be several thousand. Since it should be possible to vacuum package the device, the motion can be driven by the application of a voltage considerably less than 50 V.

Magnetic modeling was performed to find how much an applied field would be increased at the position of the sensor by the permalloy flaps as a function of the angle of the flaps. This increase will be called the enhancement. We used Maxwell 3D, a commercial finite element code from Ansoft Corp. A value of 5000 was used for the permeability except in the calculations where we considered the effect of varying the permeability. Figure 2 shows the enhancement at the position halfway between the flaps as a function of the tilt angle of the MEMS flaps about the torsional suspension for several separations between the flaps. One sees that the design provides a large modulation of the field at the position of the sensor for relatively modest angular motions. It is also clear, unfortunately, that the modulation decreases rapidly as the distance between the flaps is increased. This indicates a problem with the design. It is difficult to have much space available between the flaps for the magnetic sensor. There is, however, enough space to place a magnetoresistance sensor between the flaps. Initially a GMR sensor will be used.

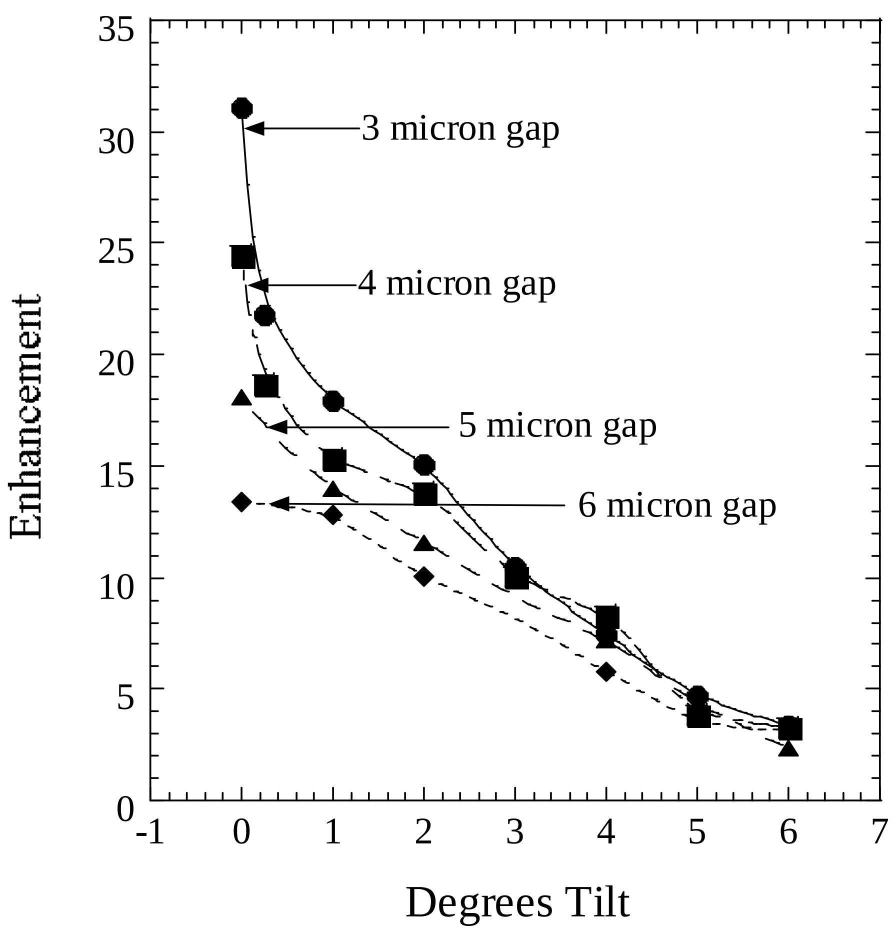

Figure 2. Enhancement of the magnetic field at the position of the magnetic sensor as a function of tilt angle of the MEMS flaps for various separations of the MEMS flaps.

Figure 3 shows the enhancement with a 3 micron gap between the flaps as a function of the permeability of the flaps when the flaps are in the plane of the sensor. One sees that for permeabilities near the values expected for permalloy (around 5000) the enhancement is a rather weak function of the permeability. Thus, it is not necessary to maximize the permeability of the permalloy. However, if the device is to be useful, it is important to minimize the *1/f* noise generated in the flux concentrator.

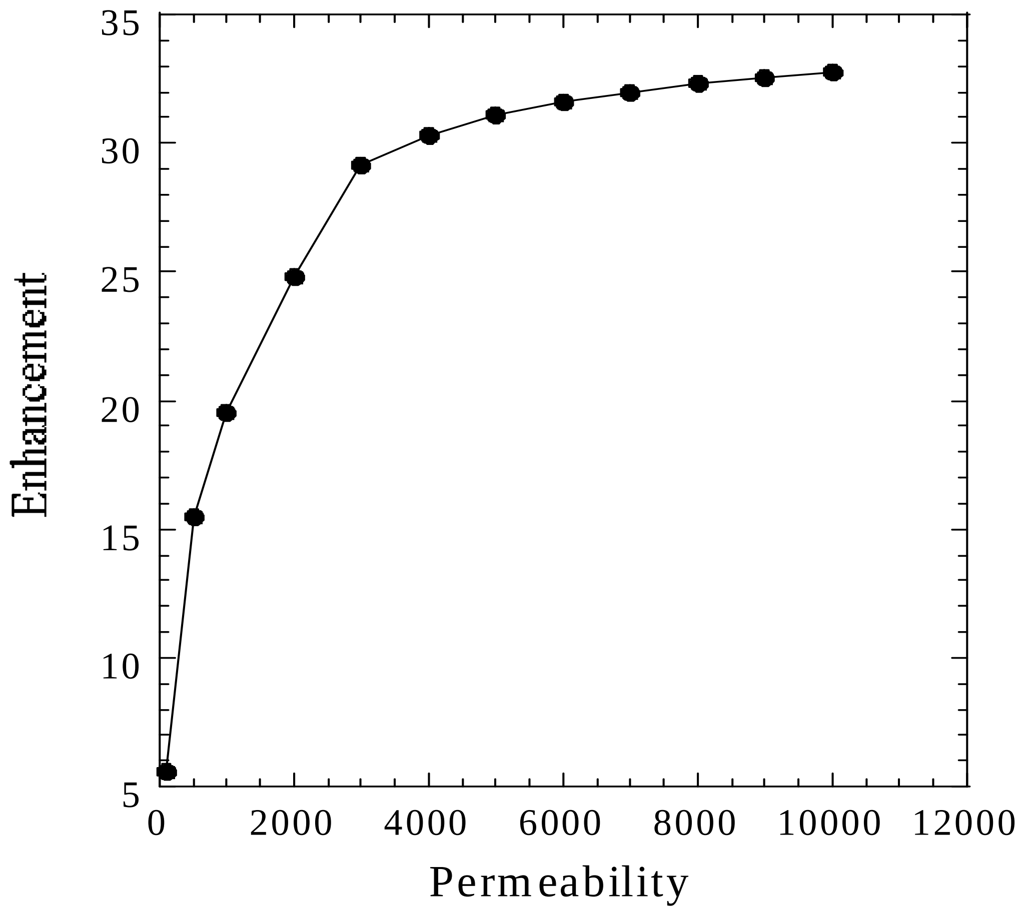

Figure3. Enhancement of the magnetic field when the MEMS flaps are in the plane of the sensor at the position of the magnetic sensor as a function of the permeability of the MEMS flaps.

We have a set of compatible fabrication and processing steps that will permit us to fabricate both the MEMS flux concentrator and a GMR magnetic sensor in close proximity on the same wafer using standard lithography techniques. The MEMS flux concentrator will be fabricated on top of a sacrificial material that fills a well made in polysilicon. The sacrificial material under the MEMS flaps will not be removed until after the GMR sensor is deposited. The temperature used to remove the sacrificial material must not be above 250 ^{o}C to prevent deterioration of the GMR sensor. This requirement limits our choice of sacrificial material. Initially we will use SiO_2 as our sacrificial material because it is compatible with MEMS technology based on polysilicon and it can be removed using room temperature etches.

A first fabrication run has been made to test the stress between polysilicon and a sputtered permalloy film. The measured compressive stress of 270 MPa would lead to significant warping. Studies have shown that the sign of the stress can be changed by annealing. Thus, it should be possible to find an annealing temperature will reduce the stress to an acceptable value.

In summary, we have described a device, a MEMS flux concentrator, that will reduce the *1/f* noise in magnetic sensors. Further, we have presented a design for a MEMS flux concentrator that will provide a large-amplitude magnetic field modulation at 29 kHz when a relatively small voltage is applied. The present design was chosen to minimize the number of difficult fabrication steps. The device will not require much power because the capacitance plates are small in area. The power consumed will be reduced by increasing the Q via vacuum packaging. The space for the magnetic sensor can be increased by increasing the distance between the MEMS flaps. In the present design, to increase the spacing between the flaps significantly without decreasing the modulation too much will require increasing the space under the plates. Increasing this space would allow larger angular motions. Fabricating a device with more space under the plates is difficult, because it is not easy to remove larger thicknesses of sacrificial material.[8] Other designs are also being considered.

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